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PATENT APPLICATION FOR

METHOD FOR FABRICATING AN ISOLATED MICROELECTROMECHANICAL  
SYSTEM (MEMS) DEVICE INCORPORATING A WAFER LEVEL CAP

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# METHOD FOR FABRICATING AN ISOLATED MICROELECTROMECHANICAL SYSTEM (MEMS) DEVICE INCORPORATING A WAFER LEVEL CAP

## CROSS-REFERENCE TO RELATED APPLICATIONS

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## BACKGROUND OF THE INVENTION

### 1. Field of the Invention

[0001] The present invention relates to microelectromechanical systems (MEMS) and, in particular, relates to the fabrication of MEMS components having a protective wafer level cap.

### 2. Discussion of the Related Art

[0002] Microelectromechanical system (MEMS) components are being progressively introduced into many electronic circuit applications and a variety of micro-sensor applications. Examples of MEMS components are electromechanical motors, radio frequency (RF) switches, high Q capacitors, pressure transducers and accelerometers. In one application, the MEMS structure is an accelerometer having a movable component that, in response to an external stimulus, is actuated so as to vary the size of a capacitive air gap. Accordingly, the capacitance output of the MEMS structure provides an indication of the strength of the external stimulus.

[0003] One method of fabricating such components, often referred to as surface micro-machining, uses a sacrificial layer such as silicon dioxide that is deposited onto a substrate which is generally single crystal silicon which has been covered with a layer of silicon nitride. A MEMS component material, polycrystalline silicon by way of example, is then deposited onto the sacrificial layer. The silicon layer is then patterned by standard photolithographic techniques and then etched by a suitable reactive ion etching plasma or by wet chemistry to define the MEMS structure and to expose the sacrificial silicon dioxide layer. The sacrificial layer is then etched to release the MEMS component. Such etching and patterning are well known by those having ordinary skill in the art, and are described, for example, in M. Madou, Fundamentals of Microfabrication, (CRC Press,

Boca Raton, 1997), or G. T. A. Kovacs, Micromachined Transducers Sourcebook, (WCB McGraw-Hill, Boston, 1998).

[0004] It is often desirable to integrate a MEMS structure with an integrated circuit into a single package or onto a single chip. However, many materials are used when fabricating an integrated circuit and during the packaging process, such as water, photoresist, dopants, coatings, etchants, epoxies, etc. The nature of MEMS structures with their inherent mechanical motion is such that the introduction of any of these materials into the structure will most likely render it inoperative. The microscopic mechanical MEMS structure may further be damaged by dirt finding its way into the structure during packaging and handling of the MEMS structure or of the integrated MEMS/circuit pair. Accordingly, a method and apparatus for protecting the MEMS structure from these potential contaminants are desirable.

[0005] What is therefore needed is a method for encapsulating a MEMS structure to protect the device from harmful contaminants and other hazards while still allowing an external electrical connection to the device.

#### BRIEF SUMMARY OF THE INVENTION

[0006] The present inventors have recognized that a cap may be bonded to a substrate so as to encapsulate a MEMS structure and provide a seal to protect the device from contaminants and other hazards.

[0007] In accordance with a first aspect of the invention, a MEMS structure includes a substrate, at least one conductive element that is in mechanical communication with the substrate and that extends therefrom, a movable MEMS element free from the substrate and positioned such that a gap separates the movable MEMS element from the at least one conductive element, at least one electrical trace having a first terminal end in electrical communication with the at least one conductive element and a second terminal end in electrical communication with a peripheral region, and a cap attached to the substrate inside the peripheral region having upper and side walls that encapsulate the at least one conductive element and the movable MEMS element.

[0008] These and other aspects of the invention are not intended to define the scope of the invention for which purpose claims are provided. In the following description, reference is made to the accompanying drawings, which form a part hereof, and in which there is shown by way of illustration, a preferred embodiment of the invention. Such

embodiment also does not define the scope of the invention and reference must be made therefore to the claims for this purpose.

### BRIEF DESCRIPTION OF THE DRAWINGS

[0009] Reference is hereby made to the following figures in which like reference numerals correspond to like elements throughout, and in which:

[0010] Fig. 1 is a sectional side elevation view of a schematic illustration of a wafer having conductive fingers disposed therein constructed in accordance with the preferred embodiment and a substrate;

[0011] Fig. 2a is a sectional side elevation view of the wafer illustrated in Fig. 1 after silicon dioxide layer deposition and photolithographic definition and etching to form vias therein;

[0012] Fig. 2b is a sectional side elevation view of the wafer illustrated in Fig. 2a after conductive polycrystalline silicon or metal deposition and photolithographic definition and etching to form the conductive fingers illustrated in Fig. 1;

[0013] Fig. 2c is a sectional side elevation view of the wafer illustrated in Fig. 2b after silicon dioxide deposition and planarization;

[0014] Fig. 3 is a sectional side elevation view of the substrate illustrated in Fig. 1 after photolithographic definition and etching;

[0015] Fig. 4 is a sectional side elevation view of the wafer bonded to the substrate of Fig. 3 to form a composite structure;

[0016] Fig. 5 is a sectional side elevation view of the composite structure illustrated in Fig. 4 with a portion of the wafer removed;

[0017] Fig. 6 is a sectional side elevation view of the composite structure illustrated in Fig. 5 having photoresist applied thereto;

[0018] Fig. 7 is a sectional side elevation view of the composite structure illustrated in Fig. 6 after photolithographic definition and etching of silicon and silicon dioxide layers and photoresist removal;

[0019] Fig. 8 is a perspective view of the schematic structure illustrated in Fig. 7;

[0020] Fig. 9 is a sectional side elevation view of the structure illustrated in Figs. 7 and 8 having a protective cap attached thereto; and

[0021] Fig. 10 is a perspective view of a plurality of mass produced caps that are configured to be installed in corresponding MEMS structures in accordance with the preferred embodiment.

#### DETAILED DESCRIPTION OF THE INVENTION

[0022] Referring initially to Fig. 1, the components of a MEMS structure constructed in accordance with the preferred embodiment include a silicon-on-insulator (SOI) wafer 20 and a substrate 22. SOI wafers of this nature are readily available commercially from manufacturers such as Shin-Etsu Handotai Co., Ltd., located in Japan. The wafer 20 includes a layer of silicon dioxide 24 that is disposed between an upper and lower layer of the silicon 26 and 28, respectively. However, as is apparent to those having ordinary skill in the art, the presence of the silicon dioxide layer 24 is not necessary for this invention, although its presence facilitates the controlled removal of layer 26 to leave a conductive layer 28 with a uniform and well-defined thickness, as will become more apparent from the description below.

[0023] A second layer of nonconductive silicon dioxide 30 is deposited onto the lowermost layer of silicon 28, and encapsulates a pair of conductive fingers 32 having first and second electrical leads 38 and 36. First lead 38 is connected via spanner member 34 to the second lead 36, which forms an electrical connection to a peripheral region of wafer 20, as will become more apparent from the description below. As the silicon dioxide layer 30 provides insulation for the conductive fingers 32 in accordance with the preferred embodiment, it should be appreciated in this regard that layer 30 could alternatively comprise any suitable generic layer that is nonconductive.

[0024] Referring now to Fig. 2a, the conductive fingers 32 are formed within the silicon dioxide layer 30 by first depositing the second layer of nonconductive silicon dioxide 30 onto the layer of silicon 28 using a standard process such as plasma enhanced chemical vapor deposition (PECVD). This layer 30 is then patterned by standard photolithographic and etching procedures using either wet chemistry or plasma etching, as is appreciated by those having ordinary skill in the art, to produce voids 31 that are disposed therein. In accordance with the preferred embodiment, the voids 31 extend through to layer 28, though the present invention includes voids of any size or shape that produce conductive fingers having two leads that are electrically connected and that facilitate the electrical

connection of the conductive element of a MEMS structure to the peripheral region, as will become more apparent from the description below.

[0025] Referring now to Fig. 2b, voids 31 will form vias that receive the deposition of a conductive material that will ultimately form the conductive fingers 32. The conductive material could be highly doped poly-silicon, a refractory metal such as tungsten, titanium, nickel, and alloys thereof or any other conductive material that will withstand the subsequent processing steps. If only low temperature steps are to follow, then a lower temperature metal, such as aluminum, could be used as the conductive material. A sufficient amount of conductive material is deposited to form the first and second leads 38 and 36.

[0026] Referring now to Fig. 2c, after the conductive layer is patterned, additional silicon dioxide is added to layer 30 so as to extend beyond the upper surface of spanner members 34 in accordance with the preferred embodiment. The surface of layer 30 is then planarized using, for example, a standard chemical-mechanical-planarization (CMP) process. The planarization may produce an upper surface comprising silicon dioxide, or layer 30 could be planarized to expose the conductive material. If the substrate is insulating, there will be no loss of isolation if the electrical traces 32 are in contact with the substrate when layer 30 is bonded to the substrate, as will be described in more detail below. It should be further appreciated that a layer of aluminum 33 (shown in phantom in Fig. 4) may be patterned onto the lower surface of layer 28 and aligned with ~~the~~ that portion of wafer 20 which will ultimately form the conductive and movable MEMS elements. The aluminum will thereby be in electrical contact with both the conductive element and lead 38 of electrical trace 32.

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[0027] Referring now to Fig. 3, the substrate 22 may comprise glass or any other insulating material, including high resistivity silicon, crystalline sapphire, or ceramic such as alumina, aluminum nitride, and the like. It should be appreciated that the substrate 22 does not necessarily have to be insulating since as described above, a sufficient amount of silicon dioxide was added to layer 30 so as to form an interface between the wafer 20 and substrate 22 that will prevent the electrical traces 32 from contacting the substrate. However, the use of an insulating substrate 22 would be desirable to achieve additional insulation, or if the nonconductive layer 30 illustrated in Fig. 2c was planarized such that spanner members 34 were exposed. If material 30 provides sufficient isolation by itself, a more conducting substrate such as crystalline silicon could be used.

[0028] Referring still to Fig. 3, a recess 40 is formed in the upper surface of the substrate 22 by placing photoresist on the substrate and patterning it so that when etched, the portion of the substrate having the photoresist disposed thereon will remain intact, while the exposed material will be removed. Accordingly, to form the recess 40 in the middle portion of the upper surface of the substrate 22, the photoresist is patterned so as to remain on the outer portions of the upper surface, and the substrate 22 is etched using a plasma etch or wet chemistry etch suitable for the material composition of the substrate, as is understood by those having ordinary skill in the art. The photoresist is then removed using the appropriate solvent for the photoresist material used. While the recess 40 is shown as being anisotropically etched in the figures, it should be appreciated that the invention includes an isotropic etching of the recess 40. The depth of recess 40 is chosen to be sufficiently large so as to enable a movable portion of the fabricated MEMS structure to release from the substrate 22 after fabrication, as will be described in more detail below. It should be appreciated that other methods exist for releasing the movable portion from the substrate, as described in a patent application entitled "Method for Fabricating an Isolated Micro-Electromechanical System Device Using an Internal Void" filed on even date herewith, the disclosure of which is hereby incorporated by reference as if set forth in its entirety herein.

[0029] Referring now to Fig. 4, the silicon dioxide layer of the wafer 20 is bonded to the upper surface of the substrate 22. In particular, the wafer 20 is positioned above the insulating substrate 22, and is bonded thereto via a high temperature fusion bonding process, or any other suitable process, as is known to those having ordinary skill in the art. Alternatively, any other suitable bonding method may be used such as epoxy, glass frit, soldering and the like. Depending on the material composition of the substrate 22, an additional layer, such as silicon dioxide or other suitable material, may need to be grown or deposited onto the upper surface thereof prior to the bonding step in order to provide a suitable layer to bond with the silicon dioxide layer 30 disposed on the bottom of wafer 20.

[0030] Referring now to Fig. 5, layer 26 of wafer 20 is removed from the top using one of many methods known by those having ordinary skill in the art. In accordance with the preferred embodiment, the substrate is ground and polished until approximately 100  $\mu\text{m}$  of layer 26 remains, and the remaining silicon is etched in tetramethylammonium hydroxide (TMAH) to expose the silicon dioxide layer 24 which serves as an etch stop.

The silicon dioxide layer 24 is then removed by etching with hydrofluoric acid. The layer 28 remains with just the desired uniform thickness, it being appreciated that the final height  $h$  of the wafer 20 will correspond generally to the desired height of the resulting fabricated MEMS structure, as will be described in more detail below. If desired, additional silicon from layer 28 may also be removed, making sure to maintain a uniform thickness of the desired height  $h$  of the wafer 20.

[0031] It should be appreciated, however, that the invention anticipates that a standard silicon wafer could be provided and etched to a desired height. However, achieving a generally uniform height in a silicon wafer can be difficult to achieve, as such wafers do not have an etch stop, such as layer 24 in the SOI wafer 20. It may nonetheless be desirable to use such standard wafers in accordance with the present invention if large volume production were desired. Such wafers may comprise silicon, silicon carbide, gallium arsenide, a high temperature metal, or alternative conductive materials suitable to withstand the subsequent fabrication processes.

[0032] An SOI wafer 20 is provided in accordance with the preferred embodiment because commercially available SOI wafers are available that differ in thickness. As a result, it is likely that a wafer may be selected whose silicon layer 28 has a height that corresponds to the desired height of the resulting fabricated MEMS structure.

[0033] Next, referring to Fig. 6, the silicon MEMS layer 28 is etched by first depositing and photolithographically patterning photoresist on the upper surface thereof. In particular, a photoresist layer is deposited and patterned to leave inner and outer photoresist members 44 and 46, such that outer photoresist members 46 are aligned with the corresponding first lead 38 of the electrical trace 32 to ultimately provide an electrical connection for the MEMS structure in accordance with the preferred embodiment.

Alternatively a silicon dioxide layer 38 may be deposited using the PECVD process, or other well-known methods, instead of photoresist to provide a mask for future etching procedures. Additionally, a gap 45, disposed between members 44 and 46, is at least partially aligned with recess 40. The recess 40 is disposed in the substrate 22 so as to allow the MEMS structure to be released from the substrate 22 upon etching.

Accordingly, layer 28 is etched into the recess, thereby releasing a movable inner MEMS element 52 (shown in Fig. 7), as will be described in more detail below. It should be appreciated that Fig. 6 is a schematic illustration whose purpose is to illustrate the conceptual placement of the photoresist in relation to the electrical traces 32 and recess



40, and could assume any configuration whatsoever that would produce a suitable MEMS structure.

[0034] Referring now to Fig. 7, the silicon layer 28 is anisotropically dry etched using a deep reactive ion etching (DRIE) process, as is understood by those having ordinary skill in the art. The etching continues until all silicon has been anisotropically etched, thereby producing outer stationary MEMS elements 50, which are termed "stationary" because they are attached to substrate 22 (albeit indirectly via layer 30). Next, the remaining photoresist is removed and a new layer of photoresist is deposited and patterned so as to define the desired structure of the silicon dioxide layer 30.

[0035] It is therefore apparent that one reason that layer 28 comprises silicon, and that layer 30 comprises silicon dioxide ~~layer~~, is because they are selectively etchable from one another, thereby facilitating the controlled patterning of both layers. It should therefore be appreciated that layers 28 and 30 could comprise any material whatsoever having the desired conductive (or nonconductive) characteristics and that are selectively etchable and suitable to be used in the construction of a MEMS structure.

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[0036] Next, the silicon dioxide layer 30 is anisotropically etched by reactive ion etching (RIE) using fluoroform or other etchant. Once the remaining photoresist is removed, the resulting product is a MEMS structure 49 having the movable inner MEMS element 52 comprising electrically conducting and electrically insulating components 28 and 30, respectively, that are released from the substrate 22 and free from the stationary outer MEMS elements 50 with a defined variable size gap 45 therebetween. In particular, the insulating component 30 for element 52 provides a base for the conducting components 28. Alternatively, the inner MEMS element could be constructed having a silicon base, as described in a patent application entitled "Method for Fabricating a MicroElectromechanical System (MEMS) Device Using a Pre-Patterned Substrate" filed on even date herewith, the disclosure of which is hereby incorporated by reference as if set forth in its entirety herein. It should be appreciated that the base could also be formed during the formation of fingers 32 and electrical leads 36 and 38.

[0037] Because the electrical traces 32 comprise a conductive material, or refractory metal in accordance with the preferred embodiment, an electrical connection is established between the stationary conductive elements 50 and the peripheral region via first and second terminals 38 and 36, respectively. The MEMS structure 49 could therefore perform any function suitable for a MEMS application. For example, the structure 49 could comprise an accelerometer whose movable MEMS element 52 is a

cantilever beam that deflects in response to external stimuli, such as an acceleration or vibration of the structure. Accordingly, as the size of the gap 45 between the stationary conductive elements 50 and the movable MEMS element 52 varies, so will the output capacitance, thereby providing a measurement of the amount of deflection of the movable MEMS element 52.

[0038] While the MEMS structure 49 constructed in accordance with the preferred embodiment is illustrated having inner movable elements 52 and outer stationary elements 50, it is easily appreciated that a MEMS structure could be constructed in accordance with the present invention whose movable elements are disposed outwardly of the stationary elements, so long as a gap exists between the movable and stationary elements to allow the capacitance to be measured, which varies as a function of the size of the gap such that deflection of the movable element with respect to the stationary element may be adequately determined. It should be easily appreciated that the present invention is equally applicable to any suitable MEMS structure.

[0039] As shown in Fig. 8, the MEMS structure 49 is exposed to the ambient environment. Accordingly, the structure 49 is subject to exposure to various contaminants and solvents that are used during subsequent handling such as structure singulation or when integrating with an integrated circuit. For example, the sensitivity of the structure 49 is such that the introduction of liquid into the immediate environment of the MEMS structure may cause the movable MEMS element 52 to deflect, thereby skewing the electrical output. In extreme cases, the introduction of liquid will cause the movable MEMS element 52 to bond with the stationary conductive elements 50, thereby rendering the structure 49 wholly inoperative. It is therefore important to protect the structure 49 from such hazards while, at the same time, establishing an electrical connection between the stationary conductive elements 50 and the peripheral region.

[0040] It should be appreciated by one having ordinary skill in the art that Fig. 8 illustrates a portion of a MEMS structure 49, it being appreciated that inner MEMS element 52 is connected to substrate 22 at its two distal ends, as disclosed in a patent application filed on March 13, 2001 and entitled "Microelectricalmechanical System (MEMS) Electrical Isolator with Reduced Sensitivity to Internal Noise" the disclosure of which is hereby incorporated by reference. For example, the void 40 that is disposed in substrate 22 may terminate, thereby connecting element 52 to the substrate. In accordance with the preferred embodiment, an elongated section of element 52 is suspended and free from the substrate, thereby permitting deflection of the free portion of

the movable MEMS element with respect to the substrate 22. An electrical trace may be connected to the movable element 52 at these connection locations.

[0041] In prior art designs, wire leads are directly attached to the stationary conductive elements 50 of a MEMS structure to render the device operational. However, such an arrangement is incapable of allowing the entire MEMS structure to be protected from the aforementioned hazards. For example, a protective cap could not be installed in this arrangement due to interference with the wire leads.

[0042] In accordance with the preferred embodiment, a wire may be connected to terminal 36 so as to place the stationary conductive elements 50 in electrical communication with the peripheral region, while at the same time removing any interference and thereby allowing a protective cap 53 to be placed on the substrate 22 and positioned at a bonding location 61, identified by the dotted lines on Fig. 8. The bonding location is disposed between the first terminal end 38 and the second terminal end 36 so that the first terminal end is exposed to the peripheral region 63 while the second end is in electrical communication with the protected stationary MEMS elements 50. It should be appreciated that the cap may comprise any material, either conducting or nonconducting, that is capable of providing the desired protection for the MEMS structure 49.

[0043] In particular, referring also to Fig. 9, the cap 53 is optically aligned with the wafer 20, and that it is bonded thereto using a suitable glass frit process, soldering process, or other bonding process as understood by those having ordinary skill in the art. Fig. 9 therefore illustrates the final device, including a protected MEMS structure 60 having a cap 53, sidewalls 54, and a height greater than the height of the stationary conductive element 50 and movable MEMS element 52. A horizontal roof 56 is attached at each end to the sidewalls 54, and end walls (not shown) are added to completely encapsulate and protect the MEMS structure 49. The cap 53 spans the entire depth of the MEMS structure 49 to completely prevent contaminants from entering the structure during subsequent processing, handling, or packaging. Additionally, the cap 53 protects the MEMS structure 49 during handling and packaging of the integrated circuit. Again, it may be observed in Fig. 9 that the stationary conductive elements 50 may be electrically connected to the peripheral region via leads 38 and 36 of the electrical trace 32. It should be appreciated in this regard that the electrical trace 32 may assume any configuration whatsoever so long as it is insulated and connected to the stationary conductive element 50 at one end, and the peripheral region at another end.

[0044] Referring to Fig. 10, a wafer 58, or blank, is illustrated having a plurality of caps 53 disposed therein. The cap wafer may be fabricated by a patterning and etching process, or any other process appropriate to the cap material, with methods understood by those having ordinary skill in the art. Accordingly, a plurality of caps may be mounted onto a corresponding plurality of MEMS structures 49 and subsequently separated, thereby facilitating the mass production of protected MEMS structures 60 in a single operation in accordance with the preferred embodiment.

[0045] The above has been described as a preferred embodiment of the present invention. It will occur to those that practice the art that many modifications may be made without departing from the spirit and scope of the invention. In order to apprise the public of the various embodiments that may fall within the scope of the invention, the following claims are made.